Composite Piezoelectric Transducer with Truncated Conical Endcaps "Cymbal"

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***Abstract*—This paper presents original results obtained in the development of the moonie-type transducers for actuator applications. The moonie-type actuators fill the gap between multilayer and bimorph actuators, but its position-dependent displacement and low generative force are unacceptable for certain applications. The moonie transducers were modified systematically by using finite element analysis combined with experimental techniques. A new transducer design, named "cymbal transducer", was developed with larger displacement, larger generative forces, and more cost-effective manufacturing. The cymbal transducers consist of a cylindrical ceramic element sandwiched between two truncated conical metal endcaps and can be used as both sensors and actuators. The cymbal actuator exhibits almost 40 times higher displacement than the same size of ceramic element. Effective piezoelectric charge coefficient, Eff. d_{33}, of cymbal is roughly 40 times higher than PZT itself.**

I. Introduction

Recently, a number of capped ceramic actuators have been developed for various applications [1]–[6]. Central to the development of these actuators has been the combination of high displacements and moderate generative forces which fill the gap between multilayer actuators and bimorph actuators. Multilayer actuators with internal electrodes exhibit high generative force, but only small displacement. Cantilever bimorph actuators exhibit large displacement, but very small generative force. These two actuators have already been commercialized [7]–[10].

This paper describes a new composite transducer, the "cymbal", with a large displacement and relatively high generative (blocking) force. The design and construction of a 12.7 mm diameter actuator with 2 mm total thickness is described, along with the displacement, generative force, and effective coupling factor. The cymbal composite actuator is then compared with other actuator designs.

II. The Method of Designing Endcaps

A. Effect of Endcap Design on Displacement

The cymbal actuator is a second generation moonie-type composite developed using FEA analysis in collaboration with experiment. Finite element analysis has identified high stress concentration in the metal endcaps just above the edge of the ceramic metal bonding layer near the edge of cavity [11]. Stress distribution diagrams in the longitudinal z-direction and in the tangential direction are shown in Figs. 1 and 2, respectively, for a moonie hydrophone, subjected to a unit hydrostatic pressure. The compressive stress concentration (13–15 units) at the inner edge of the bonding is marked with "−−" symbols. The tensile stresses appear in the region marked with "++" symbols near the outer edge of the piezoelectric ceramic.

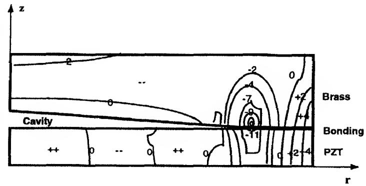

Fig. 1. Longitudinal z-directional stress distribution under hydrostatic pressure.

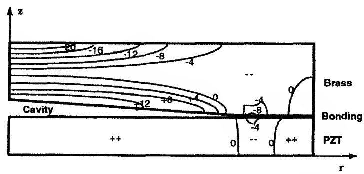

Fig. 2. Radial r-directional stress distribution under unit hydrostatic pressure. (−−) indicates compressive stresses and (++) indicates tensile stresses.

The stress concentration on the brass endcap just above the bonding layer reduces the effective force transfer from the ceramic to the cap. It is possible to eliminate part of the stress concentration by removing a portion of the endcap just above the bonding region where the maximum stress concentration is observed. An enhancement in properties has been observed by introducing a ring-shaped groove on the exterior surface of the endcaps [12].

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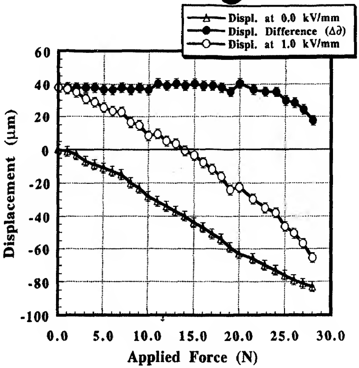

Fig. 10. Displacement-applied force relation of cymbal actuator.

The force range for the cymbal actuator is appreciably greater than that of the moonie actuator. Cymbals have a force limit of about 20 N, which is mainly controlled by the elasticity of the endcap material. By using a stiff metal for the endcap, the force limit can be increased markedly [15].

D. Electromechanical Coupling Factor and Transmission Coefficient

The electromechanical coupling factor, k, is an important parameter for piezoelectric transducers and is defined as the square root of the ratio of stored mechanical energy over input electrical energy [14]. The energy transmission coefficient, λ, is the ratio between mechanical output energy over input electrical energy, and it is a key parameter used in comparing of actuators. The relation between the electromechanical coupling factor and the maximum energy transmission coefficient is given by:

$$\lambda_{\max} = \left(\frac{1}{k} - \sqrt{\frac{1}{k^2} - 1}\right)^2. \tag{2}$$

Taking account of the maximum mechanical energy output, the energy transmission coefficient is expressed as follows:

$$\lambda = \frac{1}{2\left(\frac{2}{k^2} - 1\right)}, \tag{3}$$

which is slightly smaller than the $\lambda_{\max}$, but almost the same for the k values around 0.5.

Electromechanical coupling factors for piezoelectric ceramics are normally calculated from resonance and antiresonance frequencies. However, for the composite designs, because of their complex structure and different electrical equivalent circuits, the resonance technique is not adequate for all cases. For this reason, the input and output energy were measured, and the electromechanical coupling factors of the composite structures were calculated. To distinguish it from the materials coupling factor, the coupling factor of the composite structure is referred to as an effective electromechanical coupling factor. The energy transmission coefficient of the cymbal actuator with the dimensions given in the fabrication section was calculated as follows:

The input electrical energy, E_E, is estimated from the expression:

$$\begin{aligned} E_E &= \int iV dt = \int \frac{dQ}{dt} V dt \\ &= \int CV dV = \frac{1}{2} CV^2 \approx 1.1 \times 10^{-3} j. \end{aligned} \tag{4}$$

The dielectric constant of the PZT decreases as the applied voltage increases. As a result of this decrease, the actual capacitance is less than the low voltage capacitance value. Therefore, the electrical input energy must be less than the calculated value given by (4). For a precise calculation, the dielectric constant of PZT should be measured under an applied field up to 1.0 kV/mm. However, for simplicity the low voltage capacitance is used in these calculations. The maximum mechanical output energy, E_M, is calculated from the displacement versus applied force relation of the cymbal actuator (Fig. 10) using following equation:

$$E_M = \left(\frac{1}{2} d_{\max}\right)\left(\frac{1}{2} F_{\max}\right) = 1.3 \times 10^{-4} j \tag{5}$$

where $d_{\max}$ is the maximum displacement and $F_{\max}$ is the maximum generative force.

Therefore the energy transmission coefficient of the cymbal is equal to:

$$\lambda \approx \frac{E_M}{E_E} = 0.12. \tag{6}$$

Using (3), the effective electromechanical coupling factor, k_{eff}, of the cymbal actuator was calculated as 0.62.

As mentioned earlier, a moonie's characteristics depend on both load position (centered vs. non-centered) and contact surface (point vs. surface). For this reason the electromechanical coupling factor calculations must be completed taking both positional and contact surface dependence into consideration.

The energy transmission coefficient of a moonie actuator was calculated in a manner similar to the cymbal actuator. For a moonie actuator with the dimensions given earlier, the energy transmission factor and effective electromechanical coupling factor were calculated for a point contact at the center of the endcaps as $\lambda = 0.015$ and $k_{\text{eff}} = 0.26$, respectively. The electromechanical coupling

with grooved endcaps also showed less position-dependent behavior. For the 2 mm diameter section at the center of the samples, the effective piezoelectric coefficient is about 12,000 pC/N.

With the cymbal endcaps, the piezoelectric coefficients increased almost 60%. For a cymbal 12.7 mm in diameter and 1.7 mm in total thickness, an effective piezoelectric coefficient of more than 15,000 pC/N was measured over the 3 mm diameter center section of the cymbal transducer. We have concluded that the thick metal region near the edge of the moonie metal endcaps is a passive region which does not assist stress transfer, and acts to decrease the total efficiency. Cymbal endcaps transfer the stress more efficiently and improve the energy transfer markedly.

F. *Resonance Characteristics of the Cymbal*

The resonance spectrum of the cymbal transducer (12.7 mm in diameter and 1.7 mm thick) is shown in Fig. 12. The first resonance peak at 20.30 kHz corresponds to the flextensional mode of the composite transducer. Resonances between 150 and 160 kHz comes from the coupling between the radial mode of the PZT disc and higher order flextensional modes. Sharp resonance peaks, combined with an absence of any spurious mode, are indicative of a high quality bond between metal and ceramic. The fastest response time is an important criteria for the actuators and it can be defined as the time to achieve the quick and precise response of the actuator without overshoot and ringing. The mechanical resonance of the systems limits the practical actuation range. Actuators should be used in linear range of their resonance spectrum [17]. The fastest response time of the cymbal transducer was evaluated from: $t_{(\text{sec})} = (1/f_{\text{ft}})$, where f_{ft} is the flextensional resonance frequency. The fastest response time of the cymbal actuator is about 50 μsec.

The response time of the moonie actuator depends on the geometry of the cavity beneath the endcaps, but normally increases with increasing cavity diameter and changes only slightly with cavity depth [16]. The fastest response time is inversely proportional to the endcap thickness, and increases further with increasing compliance of the endcap material. The fastest response time of the moonie actuator is in the range of 5 to 50 μsec depending on the cavity size and endcap thickness.

IV. Discussion

A. *Comparison of the Solid State Actuator Designs*

Several features of the various solid state actuator designs are listed in Table II. It is rather difficult to compare the different actuators because of differences in geometry and various operating conditions for specific applications. To make a fair comparison, similar dimensions for each actuator were selected, and the measurement conditions are those specified in Table II. Flextensional moonie and cymbal actuators with their moderate generative force and displacement values fill the gap between multilayer and bimorph actuators. Each solid state actuator design has attractive features that can be exploited for certain applications. Advantages of the moonie and cymbal actuators are the easy tailoring of the desired actuator properties by altering the cavity size and endcap dimensions. Easy fabrication is another advantage. The rainbow actuator also partially covers this gap [5]. For that type of actuator a reduction step during processing of the ceramic element at high temperature results in a semiconducting layer and stress-bias. Even though it shows flexural motion, the rainbow can be categorized as a monomorph or a unimorph type of actuator. The effective coupling factor of rainbow is theoretically smaller than the moonie and cymbal. High applied field, position-dependent displacement and cost are the main disadvantages of the rainbow actuator in comparison with the cymbal. In the moonie and cymbal design, a multilayer piezoelectric ceramic can be used as driving element to reduce the drive voltage.

B. *Potential Applications for Moonie and Cymbal Transducers*

Moonie and cymbal actuators have great potential in the automotive industry, where they can be utilized as sensing and vibration suppression elements [18], [19]. Moonie and cymbal actuators can also be utilized as the switching element in valve designs. There is a volume change inside the moonie and cymbal transducers during cycling. This volume change can be utilized in minipump applications.

The moonie actuator can be used as a micropositioner for applications requiring small size with relatively quick response. OMRON corporation has already succeeded in using the multilayer moonie actuator for an optical scanner [20]. The high density memory storage driver such as CD-ROM driver and magneto-optic memory storage driver are other possible applications for moonie actuators capable of delivering precise positioning.

Because of their very high piezoelectric charge coefficients, moonie and cymbal transducers can be used as hydrophones, accelerometers, and air acoustic transducers. Cymbal accelerometers have more than two order of magnitude higher sensitivity than PZT ceramics at low frequencies [21]. The advantages of the cymbal type of hydrophone are very large d_h (hydrostatic charge) and g_h (hydrostatic voltage) coefficients along with lightweight and inexpensive fabrication [22].

V. Conclusion

The goals of this study were to evaluate the actuator performance of the moonie transducer, and to develop a new endcap design called the "cymbal". Displacement, generative force, and electromechanical coupling factor were used to compare the composite actuators. A die punch was designed to fabricate cymbal endcaps at min-

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